# Size of the thermal source in relativistic heavy-ion collisions*

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The dependence of the size of the thermal source on the centrality in ultrarelativistic heavy-ion collisions is studied. The interaction region consists of a well defined thermalized core, and of an outer mantle where the production scales with the number of participants. The thermal source builds up in the region with the largest density of participants in the transverse plane. Particle production in the thermalized core is enhanced in comparison to the wounded nucleon model. The change of the degree of strangeness saturation with centrality is also discussed. We perform an estimate of high $p_\perp$ jet absorption finding that an increase of the absorption in the thermal core is compatible with the data.

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## 1. Introduction

Relativistic heavy-ion collision experiments at RHIC energies $\sqrt{s} =$ 130GeV and 200GeV reveal a large degree of thermalization in the produced system. Particle spectra have thermal shapes, with a substantial amount of collective flow. The presence of a strong transverse and elliptic collective flow demonstrates the creation of a strongly interacting phase in the history of the system. This stage can be described to a large extent by an ideal hydrodynamical evolution. Particle production in heavy-ion collisions is characterized by the thermal parameters of the source : its temperature, transverse flow and possibly the degree of strangeness saturation. The temperature, the chemical potentials and the strangeness saturation at the chemical freeze-out can be extracted by fits of a statistical hadronization model to the ratios of abundances of particles produced in the central rapidity region. The description of particle spectra in transverse momentum

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requires the knowledge of the collective flow profile in the source and of the temperature at the kinetic freeze-out.

Usually it is assumed that all the produced particles are emitted from a single thermal source. One finds that the parameters of the thermal freeze-out depend on the centrality. For the chemical freeze-out one observes a significant variation of the strangeness saturation factor in peripheral collisions [1, 2]. For the kinetic freeze-out a stronger collective flow and a lower freeze-out temperature comes out from the fits to the spectra of particles in central collisions [3]. A different approach allows for spatial variations of the parameters of the freeze-out surface surface, i.e. temperature and chemical potential gradients [4].

The extraction of the thermal parameters of the source and the description of its dynamics in hydrodynamical models are useful in the description of the evolution of the dense matter produced in the collision. Such studies include the modeling of the elliptic flow in non-central collisions. Quantitative results require the knowledge of the initial conditions in the simulation. Therefore the understanding of the variation of the size and of the nature of the thermal source with centrality is crucial.

## 2. Size of the thermal source

Experimental data at the highest RHIC energies demonstrate the formation of a thermalized system in $Au+Au$ collisions : the spectra are thermal with a collective transverse flow component, the elliptic flow is compatible with an ideal fluid dynamics, particle ratios can be described by universal chemical freeze-out parameters. From the theoretical side we expect that at high energy densities formed in the collision the system undergoes a phase transition to the quark-gluon plasma. This phase transition could facilitate a complete chemical equilibration. If the partonic plasma is strongly interacting near the critical temperature, the system would behave as an ideal fluid. These feature should not vary with centrality if the thermalization and the evolution of the thermal source are dominated by the phase transition. The kinetic freeze-out is given by the local density and flow gradient and should not vary strongly with the impact parameter of the collision either.

Therefore a reasonable assumption would be to have a thermal source with the same thermal parameters at all centralities; the variation of the particle production coming only from the change of the size of the source. It has been noticed that particle production per participant in heavy-ion collisions at RHIC energies is significantly larger than in $p+p$ or $d+Au$ collisions [5, 6, 7, 8]. In the analysis of the experiments at RHIC energies Glauber Monte Carlo calculations based on the wounded nucleon picture

permit to extract the number of participants (or equivalently wounded nucleons) used to quantify the difference of the production per participant in $Au + Au$ or $d + Au$ collisions with respect to $p + p$ interactions. Geometrical scaling predicts that the bulk of the particle production, dominated by soft particles, scales with the number of wounded nucleons [9]. It has been noticed that the density of charged particles at $\eta = 0$ and the total number of charged particles produced in $d + Au$ collisions scales with the number of participants [6] :

$$\frac{dN_{dAu}}{d\eta} = N_{part} \frac{dN_{pp}}{d\eta} \ . \tag{1}$$

Remarkably, this scaling is fulfilled in a more general way by the distributions of charged particles in a broad range of pseudorapidity [10]. On the other hand particle production in $Au + Au$ collisions deviates from a simple superposition of independent production from all the wounded nucleons. The experimental data show a larger multiplicity than predicted by the scaling of the $p+p$ production by $N_{part}/2$. This and the evidence of the thermalization discussed above point to the importance of the second stage of the collision. The main characteristic of this stage is the existence of a thermally equilibrated source. Particle production from the thermal source occurs late and the production mechanism is far from the superposition of elementary collisions. In a system undergoing Bjorken longitudinal expansion the number of particles emitted at central rapidity is proportional to the transverse extension of the source. If the density of elementary collisions in the transverse plane is high one expect fast thermalization and eventually a phase transition to the quark-gluon plasma. In a geometrical Glauber model the decisive parameter is the density of wounded nucleons in the transverse plane. In peripheral collisions the density of colliding nucleons is small, and the production would be similar as in $d + Au$ collisions. In semi-central and central collisions, at the center of the interaction region the density of wounded nucleons is large and the transverse energy deposited is high enough to guaranty a fast thermalization. The boundary of the thermal source is given by the limiting density of wounded nucleons in the transverse plane sufficient for the fast thermalization processes to occur. The observation of universal chemical freeze-out parameters in $Au+Au$ collisions and the indication of the formation of a strongly interacting plasma at near critical conditions, lead to the assumption that the boundary of the thermal source and of the quark-gluon plasma phase are the same. In the outer part of the interaction region the density of participants and therfore the density of the deposited energy is not high enough to guaranty the approach of the critical point an the resulting fast thermalization. At RHIC energies the boundary in the interaction region between the thermalized source and the outer mantle is well defined by the criterion of the phase

transition. It turns out that the density of participants in the outer mantle is low, they undergo at most 2.5 binary collisions per wounded nucleon pair. A similar number of binary collision is predicted for central $d + Au$ collisions. The number of particles produced in $d + Au$ interactions (even in the most central collisions) scales with the number of participants. The low number of binary collisions in the outer mantle justifies the assumption that the number of charged particles produced in this way is proportional to the number of wounded nucleons in the mantle $N^m_{part}$.

The number of particles emitted from the source depends on the source size at the freeze-out. Since the freeze-out conditions are universal, the final number of particles produced should scale with the transverse energy deposited in the thermal source. The deposited energy is proportional to the number of wounded nucleons $N^c_{part}$ in this high density core of the interaction region. The density of charged particles produced in the central pseudorapidity region is

$$\frac{dN_{ch}}{d\eta} = \frac{N^m_{part}}{2}\frac{dN^{pp}_{ch}}{d\eta} + \frac{N^c_{part}}{2}\frac{dN^{th}_{ch}}{d\eta} \ , \tag{2}$$

where $\frac{dN^{pp}_{ch}}{d\eta}$ is the density of particles produced produced in $p + p$ collisions and $\frac{dN^{th}_{ch}}{d\eta}$ is the density per participant pair from the thermal source. The enhancement of the particle production in the thermal source can be effectively described by one parameter $\alpha$

$$\frac{dN^{th}_{ch}}{d\eta} = (1 + \alpha)\frac{dN^{pp}_{ch}}{d\eta} \ . \tag{3}$$

The number of wounded nucleons in the mantle is calculated from the formula

$$N^m_{part} = \int d^2s \frac{d\phi}{2\pi}\frac{d^2N_{part}}{ds^2}\theta(d_{cut} - \frac{d^2N_{part}}{ds^2})\Theta(\phi) \ , \tag{4}$$

where $\frac{d^2N_{part}}{ds^2}$ is the density of participants in the transverse plane, calculated from the Glauber Monte Carlo model. The integration is restricted to densities of participants lower than $d_{cut}$ and involves only particles emitted in directions other than the dense core (the function $\Theta(\phi)$ is one if the emission direction is not shadowed by the core and zero otherwise). The number of participants in the core is calculated analogously

$$\begin{aligned} N^c_{part} \ &= \ \int d^2s \frac{d\phi}{2\pi}\frac{d^2N_{part}}{ds^2}\theta(d_{cut} - \frac{d^2N_{part}}{ds^2})\,(1 - \Theta(\phi)) \\ &+ \ \int d^2s \frac{d\phi}{2\pi}\frac{d^2N_{part}}{ds^2}\theta(\frac{d^2N_{part}}{ds^2} - d_{cut}) \ , \end{aligned} \tag{5}$$

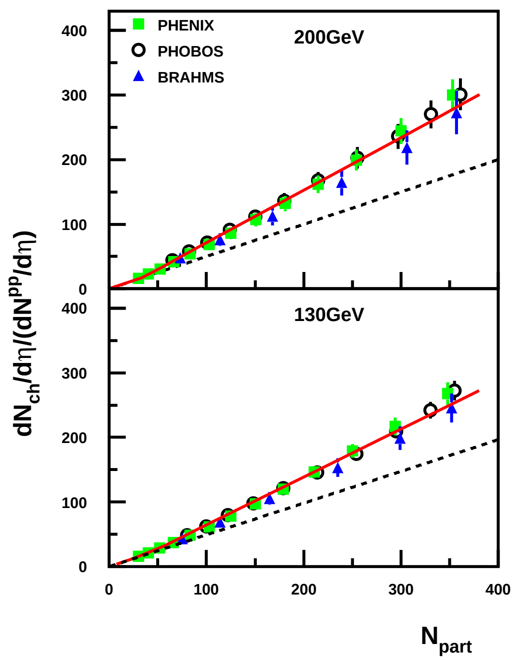


Fig. 1. Density of charged particles produced at central pseudorapidity in $Au+Au$ collisions scaled by the density of particles in $p+p$ collisions from the BRAHMS [11, 12], PHENIX [8] and PHOBOS [5, 7] experiments compared to the predictions of the core-mantle model (solid line). The dashed line represents the number of participant pairs.

the main contribution comes from the region with the density of participants larger than $d_{cut}$. For the calculation of the density of wounded nucleons we use Woods-Saxon nuclear density profiles $1/(1+\exp((r-R_A)/a))$, with parameters $a = 0.535$fm and $R_A = 1.12A^{1/3}$fm. The cross sections are $\sigma = 42$mb and 41mb for $\sqrt{s} = 200$GeV and 130GeV respectively.

The results of the calculations for the scaled particle pseudorapidity density

$$\frac{dN_{AuAu}}{d\eta} / \frac{dN_{pp}}{d\eta} \tag{6}$$

are presented in Figure 1. Published experimental data from the BRAHMS,

PHENIX and PHOBOS collaborations are shown. The density of charged particles divided by the $p + p$ density increases faster than the number of participant pairs shown by the dashed line. Moreover this increase is not exactly linear in $N_{part}$. There is a strong increase of $dN/d\eta$ around $30 - 100$ participants and then a gradual increase of the slope up to the highest centralities. We can reproduce this effect in the core-mantle model with the parameters $d_{cut} = 2\text{fm}^{-2}$ and $\alpha = 0.65$ at $\sqrt{s} = 200\text{GeV}$ and $d_{cut} = 2.2\text{fm}^{-2}$ and $\alpha = 0.5$ at $\sqrt{s} = 130\text{GeV}$. At centralities corresponding to $N_{part} = 40$ the thermalized core appears in the interaction region, causing a fast increase of the scaled particle density. For more central collisions the contribution of the thermal core in the total production increases gradually up to 95% at zero impact parameter. This leads to a slightly faster than linear increase of the particle density with the number of participants, similar as seen in the data. The increase of the production per participant pair in the core $1 + \alpha$ and the decrease of the cutoff density of participants $d_{cut}$ with energy indicate that the wounded nucleons get effectively "fatter" in the the transverse plane and deposit a larger transverse energy at higher collision energy. At SPS energies the mantle part of the interaction region is dominant. The number of binary collision in the mantle increases and the assumption of the $N^m_{part}$ scaling of the production in the mantle breaks down.

## 3. Strangeness

Following the arguments from the previous section one can argue that the production of identified strange particles in heavy-ion collisions at RHIC energies occurs by two different mechanisms in the core and in the mantle of the interaction region. In studies with a single thermal source different degree of strangeness equilibration as function of centrality is seen [1, 2]. In the core-mantle model we choose a different approach. Since the physics of the thermal core is dominated by the phase transition we assume a complete equilibration of strangeness in the thermal source, this is consistent with the data on particle ratios for the most central collisions.

Unlike the charged particle density which scales with the number of wounded nucleons in $d + Au$ collisions, the ratio $K/\pi$ depends on the centrality. Therefore, we cannot assume that in the mantle the particle ratios are similar as in $p + p$ collisions. Preliminary data from the PHENIX collaboration [13] show an increase of the $K/\pi$ ratio with the mean number of binary collisions $\nu = \frac{N_{bin}}{N_{part}/2}$. This dependence can be fitted for the $K^-/\pi^-$

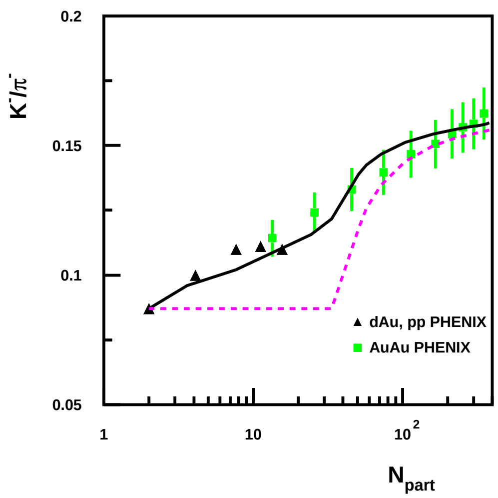


Fig. 2. $K^-/\pi^-$ ratio as a function of centrality. The data are from the PHENIX collaboration [14, 13]. The solid line denotes the sum of the emission from the thermal core and of a contribution from $p+p$ collisions scaled with the number of collisions in the mantle (equation 7). The dashed line represents the results of a calculation with a thermal source and a scaled $p+p$ contribution for the production in the mantle.

ratio by the formula

$$\left(\frac{K^-}{\pi^-}\right)_{dAu}(\nu) = 0.062 + 0.025 \times \nu \ . \tag{7}$$

Within the core-mantle model the number of produced particles can be written as

$$\begin{aligned} N_K &= \frac{N^m_{part}}{2} n^{el}_K + \frac{N^c_{part}}{2} n^{th}_K \\ N_\pi &= \frac{N^m_{part}}{2} n^{el}_\pi + \frac{N^c_{part}}{2} n^{th}_\pi \ , \end{aligned} \tag{8}$$

where $n^{el}$ and $n^{th}$ represent the production of particles per participant pair in the mantle and in the core respectively. Using $n^{th}_\pi \simeq (1+\alpha) n^{el}_\pi$, i.e. the

pion multiplicity follows the charged particles scaling, we have

$$\frac{N_K}{N_\pi} \simeq \frac{N^m_{part}\frac{n^{el}_K}{n^{el}_\pi} + (1+\alpha)N^c_{part}\frac{n^{th}_K}{n^{th}_\pi}}{N^m_{part} + (1+\alpha)N^c_{part}} \ . \tag{9}$$

The $K^-/\pi^-$ ratio in the thermal core should reproduce the experimental data for the most central collisions. We take $\frac{n^{th}_{K^-}}{n^{th}_{\pi^-}} = 0.16$ from a statistical hadronization model [15] with parameters fitted to particle ratios in central collisions. The ratio in the mantle $\frac{n^{el}_K}{n^{el}_\pi}$ is taken according to the formula (7), where $\nu$ is the average number of collisions in the mantle part of the interaction region of a $Au + Au$ collision. The results reproduce well the experimental data [14] on $K^-/\pi^-$ ratio as a function of centrality (Figure 2). The increase of strange particle production comes from the increase of the number of collisions in the mantle and from the increase of the contribution of the thermal core to the total emission. Neglecting the dependence of the ratio $\frac{n^{el}_K}{n^{el}_\pi}$ or $\left(\frac{K^-}{\pi^-}\right)_{dAu}$ on the number of collisions we cannot reproduce the centrality dependence in $d + Au$ and $Au + Au$ interactions (dashed line in Figure 2). We note that the smooth scaling of the production from peripheral $d + Au$ up to central $Au + Au$ collisions (solid line in figure 2) cannot be extended to the data for $K^+/\pi^+$.

## 4. Jet absorption

Jet quenching has been advocated as a tool for the tomography of the dense phase in the collision [16]. Experimental data show a significant suppression of jets in $Au+Au$ collisions but not in $d+Au$ interactions, suggesting that the reduction of the jet rate is due to the dense medium created in heavy-ion collisions [17, 18, 19, 20]. These results were supported by the observation of the disappearance of back to back azimuthal jet correlations in central $Au + Au$ collisions [19]. The origin of the jet suppression is the energy loss of jets or the absorption of jets in the dense matter. In the following we use a model of jet absorption [21] which can reproduce the jet suppression in the high $p_\perp$ range.

The survival probability

$$f = e^{-kI} \tag{10}$$

of a jet originating from a binary collision at $(x, y)$ and traveling in the direction $(n_x, n_y)$ depends on the density of the matter along its trajectory

$$I = \int_\tau^\infty dl \rho(x + ln_x, y + ln_y) \ , \tag{11}$$

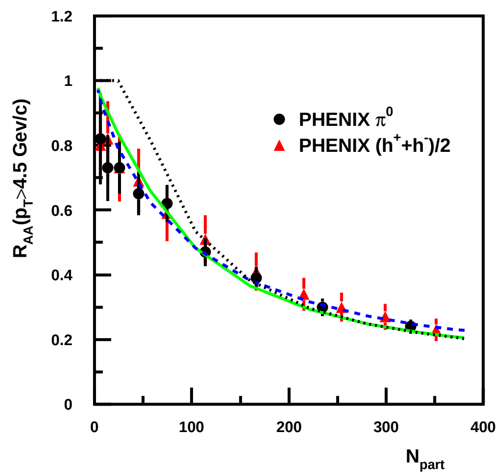


Fig. 3. $R_{AA}$ for charged hadrons and for $\pi^0$ integrated for $p_\perp > 4.5$GeV as a function of centrality [22]. The absorption only in the thermalized source is denoted by the dotted line. Absorption proportional to the wounded nucleon density is represented by the dashed line, the same is for the solid line but with an absorption increased by 65% in the thermal core.

modifications due to the longitudinal expansion and the increase of the absorption with $l$ largely cancel out and are not taken into account. Taking for the density the wounded nucleon density $\rho = d^2N_{part}/ds^2$, the jet suppression at high transverse momentum can be reproduced [21]. Using for the formation length of the jet $\tau = 0.2$fm and for the absorption coefficient $k = 0.12$fm, the PHENIX data on jet suppression [22] can be reproduced (dashed line in figure 3).

In a different scenario, it can be assumed that the absorption occurs mainly within the dense thermal core of the collision. To illustrate the effect we use the extreme limit with a large absorption within the deconfined thermal core and no absorption in the mantle. This corresponds to changing $\rho$ to $\theta(d^2N_{part}/ds^2 - d_{cut})$ in equation (11) and taking $k = 0.8\text{fm}^{-1}$ in equation (10). We use a larger value of $\tau = 0.8$fm, which corresponds in this scenario to the formation time of the thermalized opaque core. The jet suppression in the most central collisions is reproduced (dotted line in

figure 3). In peripheral collisions the thermal core disappears and the jet suppression ratio $R_{AA}$ goes to one, unlike in the data. If we believe that the dense phase is not created in peripheral collisions, this means that the jet suppression must occur in the lower density mantle part of the interaction region as well. This observation confirms the theoretical calculation of the jet suppression which increases smoothly with the density, irrespectively of the nature of the absorbing medium [23].

Finally we perform a calculation taking into account the increased density within the thermalized core. Following the increase of the particle production we take

$$\rho = \frac{d^2 N_{part}}{ds^2}\theta\left(d_{cut} - \frac{d^2 N_{part}}{ds^2}\right) + (1+\alpha)\frac{d^2 N_{part}}{ds^2}\theta\left(\frac{d^2 N_{part}}{ds^2} - d_{cut}\right) \quad (12)$$

Using the absorption coefficient $k = 0.09$fm ($\tau = 0.2$fm) we reproduce the data in the whole centrality range. This result shows that the existence of a dense core within the interaction region is compatible with the data on the jet suppression, if the absorption is proportional to the (increased) density in the core.

## 5. Conclusions

We study a model based on the separation of the interaction region in $Au + Au$ collisions in two distinct parts : a thermalized core in the most dense region and an outer mantle which is not thermalized. The inner core is rapidly thermalized when passing the region of the critical temperature and above. This includes both the kinetic and chemical equilibration. The decay of the thermal core leads to particle production per participant pair larger by 65% than in $p + p$ interactions at $\sqrt{s} = 200$GeV. The charged particle production in the mantle can be taken as in a $p + p$ collision scaled by the number of participant pairs. The thermalized core appears at around $N_{part} = 40$, we expect modifications of the density of produced particle and increased fluctuations in this range of centralities due to fluctuations in the size of the thermal source; these are not taken into account in this study. $K^-/\pi^-$ ratio as a function of centrality can be reproduced as a sum of a contribution of a chemically equilibrated thermal source and of the production from the mantle. In the mantle an increased strangeness per participant must be taken into account, following the $d + Au$ data. High $p_\perp$ jet suppression is studied in a jet absorption model. In order to reproduce the results in peripheral collisions, absorption must occur in the dense core as well as in the mantle. The increase of the density in the thermal core resulting in an increased absorption of jets is compatible with the data. Applying the model to $Cu + Cu$ collisions at $\sqrt{s} = 200$GeV we find that the

charged particle production depends on the number of participants similarly as in $Au + Au$ collisions, up to $N_{part} = 120$. However, we expect that in this case the physics could be modified by fluctuations of the relative size of the core and of the mantle.

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